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RESEARCH ARTICLE

SPECIFIC GROWTH RATE ESTIMATION FOR ANAEROBIC BIOREACTOR PROCESS MONITORING

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ABSTRACT

In this work, we are interested in the mathematical analysis of a model of a $4m^3$ bioreactor based on the results of a model already implemented ADM1. It is an observability analysis and estimation scheme for specific growth rates for an anaerobic digestion process of cow dung. A 1- *stage* model of 3 dynamic states is assumed describing all anaerobic digestion with a different population of microorganisms, and the evaluation of biogas production (methane + carbon dioxide). The result of specific growth rates ($\mu_{max} = 0.44d^{-1}$) of bacterial populations ($24gL^{-1}$ ± 2.3%) and substrate ($6.5gL^{-1}$± *0.5%)* are estimated from the dilution rate and biogas. The dynamics of anaerobic digestion appear to depend on the type of organic matter contained in cow substrates.

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INTRODUCTION

The analysis of livestock numbers in Burkina Faso reveals a large deposit of waste[1]. We have 9 million oxen, 35 million poultry, 2 million pigs, and also a lot of agricultural and invasive plants[2]. Anaerobic digestion is the decomposition of organic matter by microorganisms to produce biogas (methane and carbon dioxide) in the absence of oxygen becomes interesting [3]. Obtaining control to avoid the shutdown of biodigesters is now an important priority in research. This allows a perfect integration of wastewater treatment and waste by methanisation in the development of renewable energy in West African countries where access to energy remains less. The theology of anaerobic digestion breaks down into five stages: disintegration, hydrolysis, acidogenesis, acetogenesis, and methanogenesis [4]. Among the existing models, the number 1 model of anaerobic digestion (ADM1) remains the most credible and the most referenced with these 34 inputs and 105 outputs [5]. To arrive we consider that the bioreactor operates in continuous mode, that is to say that the input flow Q_{in} is equal to the output flowQ_{out}. We also note$D = V/Q$, the dilution rate of the system with Vthe reactor volume.

In the literature, several empirical methods following even the nature of the substrate are proposed but remain very expensive technically to express these specific growth rates. The originality of this work is to propose an even simpler method for estimating specific growth rates from quantities that are supposed to be easy to measure, such as the dilution rate and the biogas flows [6]. The objective of this study, compared to the previous ones, is to provide the estimation following a general approach to the problems of observation in differential algebraic geometry. The document is organized starting with the description of the anaerobic bioreactor studied. Then, we will describe the theory of the observability of specific growth rates with the analysis of the differential algebraic approach. Finally, the results of the estimation are illustrated. In perspective, the work will continue by strengthening the quality of the model and a comparison with experimental data.

MATERIALS AND METHODS

Presentation of the studied bioreactor: The bioreactor is an enclosure containing a nutrient medium composed of a diversity of molecules called substrates on which a variety of populations of microorganisms still known as biomass grow [7]. The biodigester of this study is a continuous volume of$4m^3$, in mesophilic operation with a temperature of$35°C$. A substrate of mass between20 kg and 30 kg mixed equitably with water is introduced each day into the reactor

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with a hydraulic retention time of $100\ days$. The anaerobic digestion (ADM1) model number 1 using 34 input variables is used to represent the bioreactor. The resulting biogas flow is $0.05\ m^3d^{-1}$ and $3.4\ m^3d^{-1}$. An identification method using the objective function showed that the biodigester is stable.

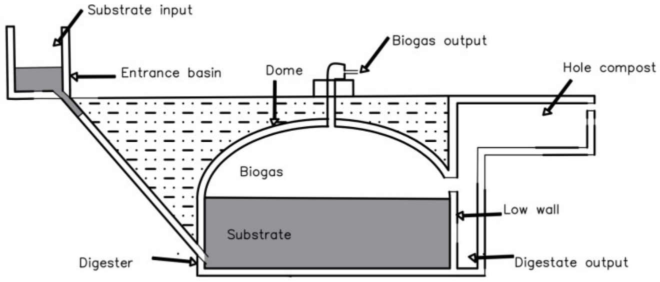

Figure 1. Model of bioreactor used in our study

Input flow dilution rate: The digester operates in continuous mode (the output flow Q_{out} = input flow Q_{in}), giving a constant culture volume. Dilution is defined as the ratio of influent flow (Qin) to reactor liquid volume (V_{liq}). The dilution obtained experimentally in 100 days is a key parameter of anaerobic digestion. Low dilution may cause the substrate to crumble and high dilution may cause the reactor to leach. The dilution rate is obtained by equation 1.

$$D = \frac{Q_{in}}{V_{liq}} \qquad \text{Equation (1)}$$

In this equation, Q_{in} = the concentration of the substrate to vent (in $m^3.d^{-1}$); V_{liq} = the liquid volume (m^3) and D = dilution flow-rate (d^{-1}).

Anaerobic Digestion Simulation Rocess

Development of the model: The whole process of anaerobic digestion of the five stages is reduced to a single stage including 3 dynamic states. Bacteria consume the substrates of cow dung to produce biogas. The dynamics are presented by the system of equations 2.

$$\begin{cases} \dot{X} = (\mu - \mathrm{D})X \\ \dot{S} = -k_1\mu\mathrm{X} + \mathrm{D}\left(\mathrm{S}_{(0)} - \mathrm{S}\right) \\ Q = k_2\mu\mathrm{X} \end{cases} \qquad \text{Equation (2)}$$

In this method, the specific growth rate of microorganisms is estimated by simply simulating the process dynamics from experimental measurements of D and Q. With X is the biomass concentration ($kgCOD.m^{-3}$), S is the substrate concentration ($kgCOD.m^{-3}$), D is the dilution rate (d^{-1}), μ is the specific growth of biogas-producing biomass (d^{-1}), $S_{(0)}$ is the concentration of influential organic pollutant ($kgCOD.m^{-3}$), k_1 and k_2 have the production coefficients that are stoichiometric parameters, and are also constant and the flow of biogas produced ($m^3.j^{-1}$).

Observability study: Observability is a method of determining or estimating the state of variables to reconstruct inaccessible states of a system. Also, the observability of a system is the property that allows one to say if the state can be determined only from the knowledge of the input and output signals. In the case of nonlinear systems, the notion of observability is unwieldy and is related to inputs and initial conditions. When in a process there are no techniques for measuring unmeasured variables, estimation techniques are then solicited. Among the approaches, differential algebraic approach methods quickly find partial answers to the problem of estimating specific growth rates of biomass based on some available measures.

The problem presented in this study, the results on the observability of the specific rate of growth of microorganisms dependent on dilution rate D, the flow of biogas Q, the initial concentration of substrate $S_{(0)}$, and the coefficients k_1 and k_2, can be accepted based on a characteristic set of differential polynomial [8]. A system {u} entry including the model parameters, {y} as the system output, {z} the estimated variable, and an epsilon {$\mathcal{E}$} the state variables. The equation system becomes the dynamics presented by equation 3.

$$\begin{cases} \dot{X} = (\mu - \mathrm{D})X = 0 \\ \dot{S} = -k_1\mu\mathrm{X} + \mathrm{D}\left(\mathrm{S}_{(0)} - \mathrm{S}\right) = 0 \\ Q = k_2\mu\mathrm{X} \\ \dot{k}_1 = 0 \\ \dot{k}_1 = 0 \end{cases} \qquad \text{Equation (3)}$$

The classification of the differential algebraic approach used gives us a $\{\{\mathbf{u},\ \mathbf{y}\},\{\mathbf{z}\},\{\varepsilon\}\} = \{\{\mathbf{D},\ \mathbf{Q},\ \mathbf{S}_{(0)},\ \mathrm{k}_1,\ \mathrm{k}_2\},\{\boldsymbol{\mu}\},\{\mathbf{X},\ \mathbf{S}\}\}$.

The derivation followed by a reduction of the system leads us to the system of equations 4.

$$\begin{cases} \dot{k}_1 = 0 \\ \dot{k}_2 = 0 \\ Q\dot{\mu} + Q\mu^2 - \dot{Q}u - DQ\mu - k_2\mu\mathrm{X} + \mathrm{Q} = 0 \\ k_2\dot{S} + k_2DS - k_2DS_{(0)} + k_1Q = 0 \end{cases} \qquad \text{Equation (4)}$$

The observability concerning parameters D, Q, $S_{(0)}$, k_1, and k_2 proves the existence of an undetermined non-differentiated polynomial being a function of D, Q, $S_{(0)}$, k_1, and k_2, as μ admits a null value. This observability would yield results according to which the biomass concentration dynamics (X) depend only on D and Sin, not dependent on the substrate concentration (S), which is an aberration. It appears that the specific growth rate of bacteria in the anaerobic digestion when the latter process evolves according to the simple model described here is not observable for D, Q, $S_{(0)}$, k_1 and k_2. The differential equation with coefficients undetermined and dependent on the derivative of D, Q, $S_{(0)}$, k_1 and k_2, of lower order is given by equation 5.

$$\dot{Q}\mu - Q\mu^2 - \dot{Q}\mu + DQ\mu = 0 \qquad \text{Equation (5)}$$

Assuming that we estimate X and S are observable from the parameters: D, Q, $S_{(0)}$, k_1, and k_2. Compared to X, the answer is positive and is directly given by the third term of the equation. The answer to S is in equation 6, describing all anaerobic digestion of beef manure at a Sin concentration with observability analysis as differential polynomials 5. The reader can refer to Baldé, Diop et al 2021[9] for further details and references on the differential-algebraic resolution methods that provide this observability test.

$$\dot{S} + DS - D\dot{S}_{(0)} + \frac{k_1}{k_2}Q \qquad \text{Equation (6)}$$

The estimation of the specific growth rate of bacteria is made from a differential algebraic approach of equation 2 and is reformulated to obtain equation 7.

$$Q\dot{\mu} + Q\mu^2 = -\dot{Q}\mu + DQ\mu \qquad \text{Equation (7)}$$

It can then be noted that in time intervals where it is not identical to zero, μ can be put in the form of the expression 8.

$$\left(\frac{Q}{\mu}\right)' = -D\left(\frac{Q}{\mu}\right) + Q \qquad \text{Equation (8)}$$

Given the quantities of D and Q are known and constant and not negative, it is possible to introduce an auxiliary variable Z defined by the quotient of biogas flows by the growth rate presented by equation 9.

$$Z = \left(\frac{Q}{\mu}\right) \qquad \text{Equation (9)}$$

The quantity Z in 10, is estimable given the exponential stability of the previous dynamic equation.

$$\begin{cases} \dot{Z} = -D(Z) + Q \\ \hat{\mu} = \dfrac{Q}{Z} \end{cases} \qquad \text{Equation (10)}$$

The equation of Z is initialized in Z (t_0) to take the initial values of the bioreactor loading presented by equation 11.

$$Z(t_0) = Z_0 = \frac{Q(t_0)}{D(t_0)} \qquad \text{Equation (11)}$$

Thus, this observer is an open-loop estimator, whose convergence is directly dictated by the strictly positive dilution rate (D). The identified parameters are calibrated using the one stage method described in Figure 2, highlighting the results of adm1 and this model in a continuous bioreactor.

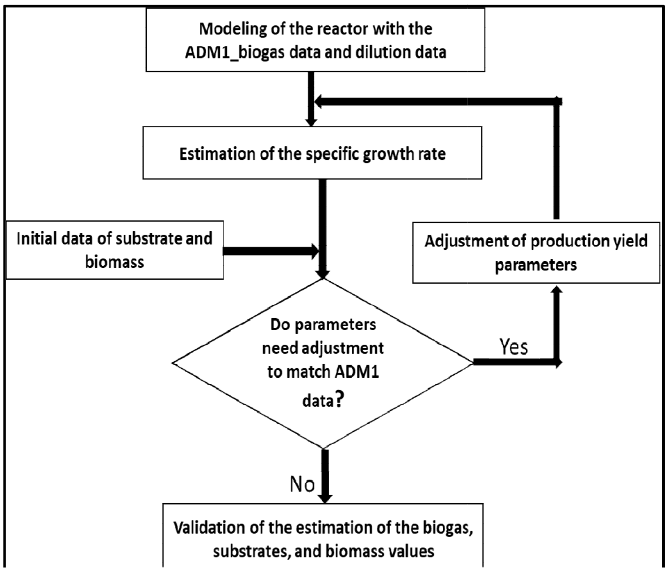

Figure 2. Calibration framework of the One-Stage model

RESULTS AND DISCUSSION

Daily profile of substrate dilution: The dilution in substrate experimentation is between 0.095d^{-1} and 0.28d^{-1} in increasing evolution over 100 days. The choice of increasing feed per piece is chosen to observe its effect on biogas production. The values of this dilution rate are shown in Figure 3.

Identification of specific growth rate: The following figures illustrate the performance of the estimator. Dilution data from Figure 3 and biogas production from ADM1 were used to feed this estimator. The specific growth rate is shown in Figure 4.

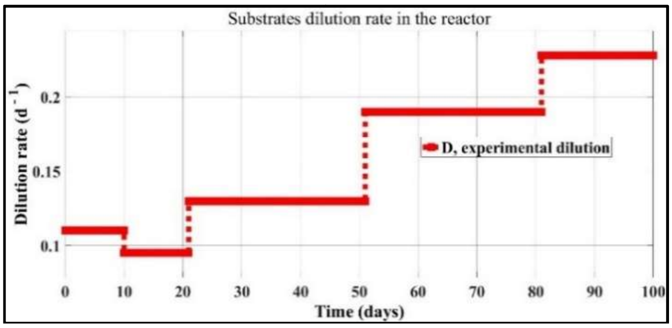

Figure 3. Profile of the dilution rate used in the experiment

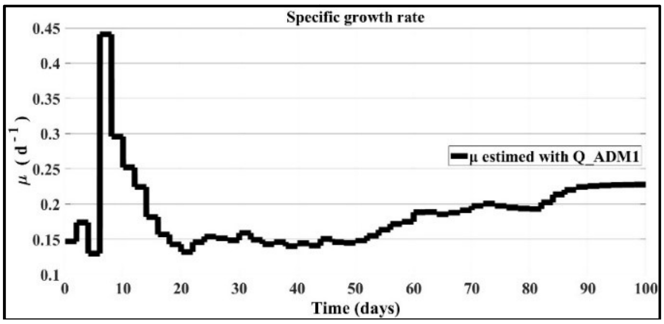

Figure 4. Specific growth rate in the reactor

The increasing and increasing value observed between 0 and 40 days that appears is due to the low output of biogas. The maximum value is $\mu_{\max} = 0.44d^{-1}$.

Identification of the rate of substrates S and biomass X: Figures 5.a and 5.b show a comparison of bacterial and substrate concentrations.

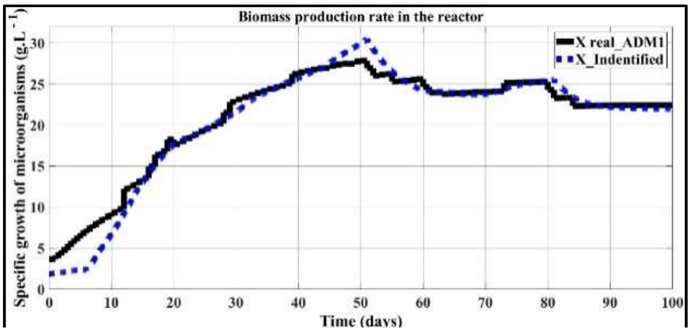

Figure 5.a

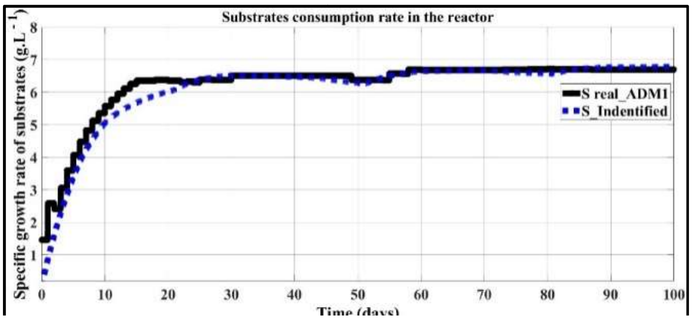

Figure 5.b

Figure 5. Evolution of growth rates of biomass X and substrates S

When the piecewise constants of the dilutionare increasing and stable, the convergence of X and S is well guaranteed between the 40th and 100th day. A fable convergence is obtained with unstable D values. Figure 5.a, from biomass X, shows that the bacteria acclimatized to the operating conditions of the bioreactor. The relative error of the mid-time estimate (50 days) is high and is around a 3% threshold. We say that the estimate of X at this level is a bit biased because it is overestimated compared to real data. The two curves are very close, especially after 70 days. We conclude that the model identifies the process implemented in ADM1.

Figure 5.b compares the results of ADM1 substrate concentrations (S) with those obtained with the identified 1-stage model to validate bioreactor performance. We find that the substrate concentration of the simplified model (maximum value = 6.4 $kg.m^{-3}$) is close to that of the ADM1 model (maximum value = 6.7 $kg.m^{-1}$ throughout the process. This makes it clear that the volume of waste to be treated by the digester must be increased. The study provided a diagnosis of the state (load) of the digester by predicting an under-load compared to the number of bacteria in the digester. In our situation, biomass production has remained constant, which prevents leaching from occurring as predicted in the Kouas study [10]. Therefore, this model helps to understand and anticipate the digester behavior.

Identification and validation of biogas production: The comparison of biogas production with both models is illustrated in Figure 6.

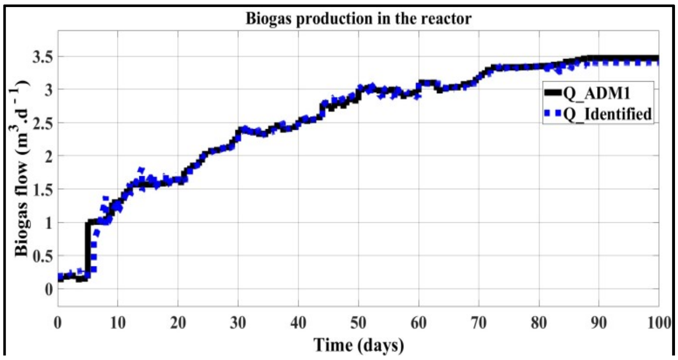

Figure 6. Daily flow rate of biogas produced in the reactor

The 4m^3 biodigester produced an average flow rate of 2.5 m^3d^{-1} ± 0.2% with the two ADM1 models and the simplified model. Therefore, any lower production in the future is due either to a malfunction of the bioreactor or a sharp variation in the composition of organic matter. At this moment a correction becomes necessary. To solve the dynamics of the system of differential equations, initial conditions, the method of which is called estimates or model adjustment to obtain consistent results. To estimate the parameters, a *S- function* in *Matlab / Simulink* ®2021 (License No: 595687) allowed to write computer codes of mathematical formulas in language C. The initial parameters of the substrate $S_{(0)}$= 0.05gL^{-1} and bacteria is X_{in} =1.88 gL^{-1}. The parameters of the growth of the bioreactor k_1= 0.06 g/L and k_2= 0.68 gL^{-1}, and the saturation coefficient K_s= 2.32 gL^{-1}.

CONCLUSIONS

In this work, we studied a model of substrate degradation in a reduced bioreactor of 4m^3. Using the differential algebraic approach of observability and algebraic methods, we have demonstrated that specific growth rates of cow waste are estimated from experimentally measured data (dilution rate D and biogas flow rate). This saves time in empirical modeling and the identification of specific growth rates, and allows the use of a wide variety of wastes without repeating this empirical modeling. The originality of this work allowed us to highlight the substrate rates necessary for the degradation of a quantity of substrates to obtain qualitative behaviors on the leaching of species and possible inhibition of substrates. In addition, we can say that this One-Stage estimate will become a valuable tool for the control and monitoring of anaerobic digestion processes for design offices and large-scale facilities. The modeling thus illustrated the verifiable mathematical results.

Author contributions: NB designed the study, developed the simulation, and wrote the manuscript. YMB performed the parametric identification work, DWNK designed the study on biogas production calculations of cow substrates, and revised the manuscript. Author SD took over the quality verification simulation of the estimator and wrote the reviews of the manuscript, SK and IO analyzed the results and adjusted the model parameters. All authors reviewed and approved the complete manuscript.

Conflict of Interest Statement: The authors declare no conflicts of interest.

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